8813

NASA Technical Memorandum 87692

Optical Model Calculations of Heavy-Ion Target Fragmentation

Lawrence W. Townsend, John W. Wilson,
Francis A. Cucinotta, and John W. Norbury

JULY 1986

(NASA-TM-87692) OPTICAL MODEL CALCULATIONS OF HEAVY-ION TARGET FRAGMENTATION (NASA) 15 p HC A02/MF A01 CSCL 20H
N86-27063
Unclas
G3/73 43416

NASA

NASA Technical Memorandum 87692

Optical Model Calculations of Heavy-Ion Target Fragmentation

Lawrence W. Townsend and John W. Wilson
Langley Research Center
Hampton, Virginia

Francis A. Cucinotta and John W. Norbury
Old Dominion University
Norfolk, Virginia

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1986

Introduction

In the approaching era of career astronauts and space workers who will man the Space Station, knowledge of galactic cosmic-ray interaction and transport in bulk matter is required to accurately analyze requirements for shielding from space radiation and to adequately assess the resulting radiobiological damage to the astronauts themselves. In previous work (refs. 1 and 2 and references cited therein), a simple theory of projectile heavy-ion fragmentation based upon an abrasion-ablation model was presented. For the abrasion step, a quantum mechanical formalism based upon an optical model potential approximation was used (ref. 3). The charge dispersions of the excited projectile prefragments were calculated by both a hypergeometric distribution and a method based upon the zero-point oscillations of the giant dipole resonance (ref. 4). The excitation energies of the projectile prefragments were estimated from the geometric "clean-cut" model (ref. 5). In the ablation stage of the fragmentation process, compound nucleus decay probabilities for the various particle emission channels of the excited prefragment were calculated by the Monte Carlo program EVAP-4, which was developed at Oak Ridge National Laboratory (ref. 6).

In this work, the simple theory of projectile heavy-ion fragmentation is extended to include the effects of Coulomb dissociation (ref. 7) and frictional spectator interactions (FSI) (ref. 8) and then applied to the study of fragmentation of target nuclei by relativistic protons and heavy ions. Target nucleus fragmentation is of interest to the galactic heavy-ion shielding problem because of its relevance to radiobiological damage studies and because it represents a substantial source of experimental data suitable for validating our heavy-ion fragmentation theory.

Target Fragmentation Theory

Since the underlying physical concepts applicable to the abrasion-ablation fragmentation model have been discussed elsewhere (refs. 1 and 2), they are not repeated herein. Instead, a brief outline of the calculational methods, as they are used to predict target fragmentation cross sections, is described in the following subsections. For more detailed discussions, the reader is urged to consult the references. The validity of using the projectile fragmentation theory to also describe target fragmentation rests upon the underlying assumptions of the abrasion-ablation model (ref. 8) and the symmetry between projectile and target ions inherent in our optical model formalism (ref. 2). A flow diagram of the calculational steps involved in predicting target nucleus fragmentation cross sections is given in figure 1.

Abrasion Cross Sections

Interchanging target and projectile nuclei in the expressions presented in reference 1 gives the cross section for abrading m target nucleons as

$$\sigma_m = \binom{A_T}{m} \int d^2\mathbf{b}\; [1 - P(\mathbf{b})]^m \; P(\mathbf{b})^{A_F} \tag{1}$$

where the probability of not removing a target nucleon in the collision is (ref. 1)

$$P(\mathbf{b}) = \exp[-A_P \; \sigma(e) \; I(\mathbf{b})] \tag{2}$$

with

$$I(\mathbf{b}) = [2\pi \; B(e)]^{-3/2} \int dz_0 \int d^3\boldsymbol{\xi}_P \; \rho_P(\boldsymbol{\xi}_P) \times \int d^3\mathbf{y} \; \rho_T(\mathbf{b} + \mathbf{z}_0 + \mathbf{y} + \boldsymbol{\xi}_P) \exp\left[\frac{-y^2}{2\,B(e)}\right] [1 - C(\mathbf{y})] \tag{3}$$

and prefragment mass number

$$A_F = A_T - m \tag{4}$$

(Definitions of symbols and abbreviations used in this paper appear after the references.) Methods for determining the appropriate projectile and target nuclear distributions ρ_i and constituent-averaged nucleon-nucleon cross sections $\sigma(e)$ are described in references 9 and 10. Values for the nucleon-nucleon scattering slope parameter are obtained from the appropriate parameterization for diffractive scattering, which is given in reference 11. As before (refs. 1 and 2), the Pauli correlation is

$$C(\mathbf{y}) = 0.25 \exp\left(\frac{-k_F^2 y^2}{10}\right) \tag{5}$$

where

$$k_F = 1.36 \text{ fm}^{-1}$$

Prefragment Charge Distributions

Since the abraded nucleons consist of protons and neutrons, which are not identical, a prescription for calculating the charge dispersions of the prefragments is needed to calculate final, isotope, and/or elemental production cross sections caused by the fragmentation process. Two such methods are used in the fragmentation theory described in this work.

The first method (ref. 1) treats the neutron and proton distributions as completely uncorrelated. The cross section for forming a particular prefragment of mass A_j and charge Z_j is then given in terms of the cross section for abrading m nucleons σ_m as

$$\sigma_{\rm abr}(Z_j, A_j) = \frac{\binom{N}{n}\binom{Z}{z}}{\binom{A_T}{m}}\sigma_m \tag{6}$$

where z of the original Z target nucleus protons are abraded along with n of the original N target neutrons. Note that

$$A_T = N + Z \tag{7}$$

and

$$m = n + z \tag{8}$$

with

$$Z_j = Z - z \tag{9}$$

and

$$A_j = A_T - m \tag{10}$$

The hypergeometric distribution is based on the assumption that there is no correlation at all between neutron and proton distributions. Therefore, unphysical results such as abrading all neutrons or protons from a nucleus while leaving the remaining fragment intact could occur.

As an alternative to the hypergeometric distribution, Morrissey et al. (ref. 4) proposed a charge dispersion model based upon the zero-point vibrations of the giant dipole resonance of the target nucleus. In this model, equation (6) becomes

$$\sigma_{\rm abr}(Z_j, A_j) = N_j (2\pi\alpha_Z^2)^{-1/2} \exp \frac{-[Z_j - A_j(Z/A_T)]^2}{2\alpha_Z^2}\sigma_m \tag{11}$$

where the variance (dispersion) is

$$\alpha_Z = 2.619 \left(\frac{u}{A_T}\right)^{1/2} \left(\frac{Z}{A_T}\right) \left(\frac{dm}{db}\right) (1+u)^{-3/4} \tag{12}$$

with

$$u = \frac{3J}{Q(A_T)^{1/3}} \tag{13}$$

In the droplet model of the nucleus, the coefficients J and Q have the nominal values of 25.76 MeV and 11.9 MeV, respectively (ref. 4). The rate of change of the number of nucleons removed as a function of impact parameter (dm/db) is calculated numerically by using the geometric abrasion model of reference 12. The normalization factor N_j insures that for a given value of A_j, the discrete sum over all allowed values of Z_j yields unity for the dispersion probabilities.

Prefragment Excitation Energies

The excitation energies of the target prefragments after abrasion of m nucleons are assumed to be given by

$$E_{\rm exc} = E_{\rm surf} + E_{\rm FSI} \tag{14}$$

where $E_{\rm surf}$ is the surface energy calculated from the clean-cut abrasion formalism, and $E_{\rm FSI}$, the contribution from frictional spectator interactions, is estimated by the methods in reference 8. For completeness, the calculational details are included in this work.

From the clean-cut abrasion formalism (ref. 1), the surface energy term is

$$E_{\rm surf} = \Delta \cdot E_s \tag{15}$$

where the liquid drop nuclear model surface energy coefficient E_s is 0.95 MeV/fm^2, and the excess surface area of the misshapen nucleus (following abrasion) is

$$\Delta = 4\pi R_T^2[1 + P - (1-F)^{2/3}] \tag{16}$$

The expressions for P and F vary for different types of collisions (peripheral or central) and for different relative sizes of the colliding nuclei. The target fragmentation expressions for P and F are obtained from equations (15) through (27) of reference 1 by interchanging R_T and R_P. For peripheral collisions $(R_P - R_T \le b \le R_P + R_T)$ where $R_P > R_T$ we have

$$\begin{aligned} P = {} & 0.125(\mu\nu)^{1/2}\left(\frac{1}{\mu} - 2\right)\left(\frac{1-\beta}{\nu}\right)^2 \\ & - 0.125[0.5(\mu\nu)^{1/2}\left(\frac{1}{\mu} - 2\right) + 1]\left(\frac{1-\beta}{\nu}\right)^3 \end{aligned} \tag{17}$$

and

$$F = 0.75(1-\nu)^{1/2}\left(\frac{1-\beta}{\nu}\right)^2 - 0.125[3(1-\nu)^{1/2} - 1]\left(\frac{1-\beta}{\nu}\right)^3 \tag{18}$$

with

$$\nu = \frac{R_T}{R_P + R_T} \tag{19}$$

$$\beta = \frac{b}{R_P + R_T} \tag{20}$$

and

$$\mu = \frac{1}{\nu} - 1 = \frac{R_P}{R_T} \tag{21}$$

If the collision is central, then the target volume completely overlaps the projectile volume

($b < R_P - R_T$), and all the target nucleons are abraded. In this case, equations (17) and (18) are replaced by

$$P = -1 \tag{22}$$

and

$$F = 1 \tag{23}$$

and there is no ablation of the target, since it was destroyed by the abrasion.

For the case where $R_T > R_P$ and the collision is peripheral, equations (17) and (18) become

$$\begin{aligned} P = 0.125(\mu\nu)^{1/2}\left(\frac{1}{\mu}-2\right)\left(\frac{1-\beta}{\nu}\right)^2 - 0.125\Bigg\{0.5\left(\frac{\nu}{\mu}\right)^{1/2} \\ \times\left(\frac{1}{\mu}-2\right) - \frac{[(1/\nu)(1-\mu^2)^{1/2}-1][(2-\mu)\mu]^{1/2}}{\mu^3}\Bigg\} \\ \times\left(\frac{1-\beta}{\nu}\right)^3 \end{aligned} \tag{24}$$

and

$$\begin{aligned} F = 0.75(1-\nu)^{1/2}\left(\frac{1-\beta}{\nu}\right)^2 - 0.125\Bigg\{\frac{3(1-\nu)^{1/2}}{\mu} \\ - \frac{[1-(1-\mu^2)^{3/2}][1-(1-\mu)^2]^{1/2}}{\mu^3}\Bigg\}\left(\frac{1-\beta}{\nu}\right)^3 \end{aligned} \tag{25}$$

where the impact parameter is restricted such that

$$R_T - R_P \le b \le R_P + R_T \tag{26}$$

For a central collision ($b < R_T - R_P$) with $R_T > R_P$, equations (24) and (25) become

$$P = \left[\frac{1}{\nu}(1-\mu^2)^{1/2} - 1\right]\left[1-\left(\frac{\beta}{\nu}\right)^2\right]^{1/2} \tag{27}$$

and

$$F = [1-(1-\mu^2)^{3/2}]\left[1-\left(\frac{\beta}{\nu}\right)^2\right]^{1/2} \tag{28}$$

In the abrasion process, some of the abraded nucleons are scattered into, rather than away from, the prefragment. This scattering results in the deposition of additional excitation energy by these so-called "frictional spectator interactions." From reference 8, the excitation energy due to p frictional spectator interactions is

$$E_{\mathrm{FSI}} = p < E_{\mathrm{dep}} > \tag{29}$$

where p, the number of abraded nucleons scattered into the prefragment, takes on integer values from 0 to m, and $< E_{\mathrm{dep}} >$ is the average energy deposited by any of the p nucleons. From reference 8, the rate that energy E (in megaelectronvolts, MeV) is deposited by an interacting nucleon traversing a distance x into the prefragment is

$$\frac{dE}{dx} = -\frac{E}{4\lambda} \tag{30}$$

where the mean free path is

$$\lambda = (\rho\sigma_{NN})^{-1} \tag{31}$$

with an assumed nuclear density of $\rho = 0.17\ \mathrm{fm}^{-3}$ and an approximate nucleon-nucleon cross section (in femtometers squared, fm^2) given by

$$\sigma_{NN} \approx \frac{300}{E} \tag{32}$$

Since the maximum deposited energy occurs when the abraded nucleon traverses a target nucleus diameter, then

$$E_{\max} = 2R_T\left|\frac{dE}{dx}\right| \tag{33}$$

where the uniform density target nucleus radius is

$$R_T = r_0 A_T^{1/3} \tag{34}$$

and $r_0 = 1.2$ fm. In terms of the maximum deposited energy, the average deposited energy, obtained from

$$< E_{\mathrm{dep}} > = \pi^{-1}\int_0^{\pi} E_{\mathrm{dep}}(\theta)\, d\theta \tag{35}$$

is

$$< E_{\mathrm{dep}} > \approx \frac{1}{3}E_{\max} \tag{36}$$

where θ is the angle describing the orientation of the trajectory of the abraded nucleon with respect to its diameter within the prefragment. Substituting equations (30) through (34) into equation (36) yields

$$< E_{\mathrm{dep}} > \approx 10.2 A_T^{1/3} \tag{37}$$

If one assumes that each abraded nucleon, on the average, has a 50-percent probability of being scattered back into the target prefragment, then each prefragment with mass number A_j and charge number Z_j which has experienced p frictional spectator interactions has an abrasion cross section given by

$$\sigma_{\mathrm{abr}}(Z_j, A_j, p) = \frac{\binom{m}{p}}{2^m}\,\sigma_{\mathrm{abr}}(Z_j, A_j) \tag{38}$$

with $\sigma_{\text{abr}}(Z_j, A_j)$ given by either equation (6) or equation (11).

Ablation Factors

Depending upon the excitation energy, the decay of the excited prefragment may occur by emission of one or more nucleons (protons or neutrons), composites (deuterons, tritons, ^{3}He, or alpha particles), or gamma rays. The probability α_{ij} for formation of a particular final fragment of type i as a result of the deexcitation of a prefragment of type j is obtained from the EVA-3 computer code (ref. 12). The final nuclear fragmentation cross section for production of the type-i isotope is then given by

$$\sigma_{\text{nuc}}(Z_i, A_i) = \sum_j \sum_{p=0}^{m} \alpha_{ij}\ \sigma_{\text{abr}}(Z_j, A_j, p) \qquad (39)$$

where $\sigma_{\text{abr}}(Z_j, A_j, p)$ is obtained from equation (38). To compare these predictions with experimental data, one must also include contributions due to Coulomb dissociation (ref. 7) to yield a cross section for production of a final fragment with charge number Z_i and mass number A_i as

$$\sigma_F(Z_i, A_i) = \sigma_{\text{nuc}}(Z_i, A_i) + \sigma_{EM} \qquad (40)$$

Elemental production cross sections are obtained by summing over all isotope contributions as

$$\sigma_Z(Z_i) = \sum_{A_i} \sigma_F(Z_i, A_i) \qquad (41)$$

Results

Cross sections for the production of carbon, boron, beryllium, and lithium isotopes in the fragmenting of carbon target nuclei by relativistic carbon, neon, and iron projectile nuclei are listed in tables I to III. Displayed are theoretical predictions using both the hypergeometric (eq. (6)) and giant dipole resonance (eq. (11)) charge dispersion models. The experimental results for carbon-carbon collisions (in table I) are taken from references 13 and 14. The reference 13 cross sections are actually for fragmentation of the carbon projectile, rather than the carbon target, but are useful for comparison purposes. In general, as shown in table I, the giant dipole resonance model yields better agreement with experimental data. Tables II and III show reasonable agreement between theory and experimental values (ref. 15) for the ^{11}C production cross sections, but the lack of data on experimental cross sections for other isotopes precludes further meaningful comparison. For all three collisions, the theoretical cross sections were calculated by using the steps displayed in figure 1.

In table IV, representative cross sections for the fragmentation of copper targets by high-energy protons are displayed. Giant dipole resonance charge dispersions were not calculated, since the correct value to use for the proton radius is not clear. Choosing a value ($\approx$ 1 fm) based upon the proton charge radius yielded unphysical values for α_z (eq. (12)). In addition, negative values for E_{surf} (eq. (15)) were obtained with protons because of the approximate nature of equations (17) and (18). Therefore, we assumed that $E_{\text{surf}} = 0$ for protons and used

$$E_{\text{exc}} = E_{\text{FSI}} \qquad (42)$$

in the p + ^{64}Cu calculations. Much of the disagreement between theory and experimental values (ref. 16), however, results from the "cumulative" nature of the experimental cross sections. These cross sections were obtained by counting the irradiated target samples after periods of time ranging from several hours to several days. Hence, most of the short-lived isotopes produced in the fragmentations decayed prior to counting. A more realistic method of comparison would be to correct the theoretical results for these decays and predict "cumulative" cross sections. This comparison was not done, however, because cumulative cross sections are of very limited usefulness in radiobiological applications of the fragmentation theory.

As suggested by these results, future improvements to the fragmentation theory will center on developing correct methods for estimating the prefragment excitation energy. One possibility which will be explored is the impulsive excitation model of reference 17.

Concluding Remarks

A simple abrasion-ablation model for describing heavy-ion fragmentation has been extended to include frictional spectator interaction effects and applied to target nucleus fragmentation processes. The model was shown to yield reasonable agreement with experimental isotope production cross sections obtained at Lawrence Berkeley Laboratory in collisions of relativistic carbon, neon, and iron projectiles with carbon targets. Predictions of target fragmentation cross sections for proton-copper collisions were also made. For nucleus-nucleus fragmentations, the giant dipole resonance charge dispersions appeared to yield better agreement between theory and experiment than the hypergeometric model. The major shortcoming of the fragmentation model, at this time, appears to be the methods used to estimate the prefragment excitation energies.

NASA Langley Research Center
Hampton, VA 23665-5225
March 27, 1986

References

1. Townsend, Lawrence W.; Wilson, John W.; Norbury, John W.; and Bidasaria, Hari B.: *An Abrasion-Ablation Model Description of Galactic Heavy-Ion Fragmentation.* NASA TP-2305, 1984.
2. Townsend, L. W.; Wilson, J. W.; and Norbury, J. W.: A Simplified Optical Model Description of Heavy Ion Fragmentation. *Canadian J. Phys.*, vol. 63, no. 2, Feb. 1985, pp. 135–138.
3. Townsend, L. W.: Abrasion Cross Sections for ^{20}Ne Projectiles at 2.1 GeV/Nucleon. *Canadian J. Phys.*, vol. 61, no. 1, Jan. 1983, pp. 93–98.
4. Morrissey, D. J.; Marsh, W. R.; Otto, R. J.; Loveland, W.; and Seaborg, G. T.: Target Residue Mass and Charge Distributions in Relativistic Heavy Ion Reactions. *Phys. Rev.*, ser. C, vol. 18, no. 3, Sept. 1978, pp. 1267–1274.
5. Gosset, J.; Gutbrod, H. H.; Meyer, W. G.; Poskanzer, A. M.; Sandoval, A.; Stock, R.; and Westfall, G. D.: Central Collisions of Relativistic Heavy Ions. *Phys. Rev.*, ser. C, vol. 16, no. 2, Aug. 1977, pp. 629–657.
6. Guthrie, Miriam P.: *EVAP-4: Another Modification of a Code To Calculate Particle Evaporation From Excited Compound Nuclei.* ORNL-TM-3119, U.S. At. Energy Comm., Sept. 10, 1970.
7. Norbury, John W.; and Townsend, Lawrence W.: *Electromagnetic Dissociation Effects in Galactic Heavy-Ion Fragmentation.* NASA TP-2527, 1986.
8. Oliveira, Luiz F.; Donangelo, Raul; and Rasmussen, John O.: Abrasion-Ablation Calculations of Large Fragment Yields From Relativistic Heavy Ion Reactions. *Phys. Rev.*, ser. C, vol. 19, no. 3, Mar. 1979, pp. 826–833.
9. Townsend, Lawrence W.; Wilson, John W.; and Bidasaria, Hari B.: *Heavy-Ion Total and Absorption Cross Sections Above 25 MeV/Nucleon.* NASA TP-2138, 1983.
10. Townsend, Lawrence W.; Wilson, John W.; and Bidasaria, Hari B.: *Nucleon and Deuteron Scattering Cross Sections From 25 MeV/Nucleon to 22.5 GeV/Nucleon.* NASA TM-84636, 1983.
11. Ringia, F. E.; Dobrowolski, T.; Gustafson, H. R.; Jones, L. W.; Longo, M. J.; Parker, E. F.; and Cork, Bruce: Differential Cross Sections for Small-Angle Neutron-Proton and Neutron-Nucleus Elastic Scattering at 4.8 GeV/c. *Phys. Rev. Lett.*, vol. 28, no. 3, Jan. 17, 1972, pp. 185–188.
12. Morrissey, D. J.; Oliveira, L. F.; Rasmussen, J. O.; Seaborg, G. T.; Yariv, Y.; and Fraenkel, Z.: Microscopic and Macroscopic Model Calculations of Relativistic Heavy-Ion Fragmentation Reactions. *Phys. Rev. Lett.*, vol. 43, no. 16, Oct. 15, 1979, pp. 1139–1142.
13. Lindstrom, P. J.; Greiner, D. E.; Heckman, H. H.; Cork, Bruce; and Bieser, F. S.: *Isotope Production Cross Sections From the Fragmentation of ^{16}O and ^{12}C at Relativistic Energies.* LBL-3650 (NGR-05-003-513), Lawrence Berkeley Lab., Univ. of California, June 1975.
14. Smith, A. R.; McCaslin, J. B.; Geaga, J. V.; Hill, John C.; and Vary, J. P.: Cross Sections for the Production of ^{11}C in C Targets by ^{12}C at Relativistic Energies. *Phys. Rev.*, ser. C, vol. 28, no. 4, Oct. 1983, pp. 1614–1617.
15. Hill, John C.; Winger, J. A.; McCullough, C. M.; Smith, A. R.; McCaslin, J. B.; and Karol, P. J.: Production of ^{11}C in C Targets by Relativistic Heavy Ions with $Z \leq 26$. *Bull. American Phys. Soc.*, vol. 30, no. 8, Sept. 1985, p. 1262.
16. Cumming, J. B.; Haustein, P. E.; Stoenner, R. W.; Mausner, L.; and Naumann, R. A.: Spallation of Cu by 3.9-GeV ^{14}N Ions and 3.9-GeV Protons. *Phys. Rev.*, ser. C, vol. 10, no. 2, Aug. 1974, pp. 739–755.
17. Bayman, B. F.; Ellis, P. J.; Fricke, S.; and Tang, Y. C.: Anomalon Production by Impulsive Excitation in Relativistic Heavy-Ion Collisions. *Phys. Rev. Lett.*, vol. 53, no. 14, Oct. 1, 1984, pp. 1322–1324.

Symbols

A_F	prefragment nuclear mass number
A_i	nuclear mass number for *ith* nucleus
A_P	projectile nuclear mass number
A_T	target nuclear mass number
$B(e)$	average slope parameter of nucleon-nucleon scattering amplitude, fm^2
$\mathbf{b}$	target impact parameter, fm
$C(\mathbf{y})$	Pauli correlation function, defined in equation (5)
E_{dep}	energy deposited by nucleon undergoing FSI
E_{exc}	target prefragment excitation energy, MeV
E_{FSI}	frictional spectator interaction excitation energy, MeV
E_{max}	maximum deposited energy, MeV
E_s	nuclear surface energy coefficient, MeV/fm^2
E_{surf}	nuclear surface excitation energy, MeV
e	two-nucleon kinetic energy in their center of mass frame, GeV
F	function defined in equations (18), (23), (25), and (28)
FSI	frictional spectator interaction
$I(\mathbf{b})$	defined in equation (3)
J	droplet model coefficient (25.76 MeV)
m	number of abraded nucleons
N	total number of nuclear neutrons
N_j	renormalization coefficient for *jth* prefragment
n	number of abraded neutrons
P	function defined in equations (17), (22), (24), and (27)
$P(\mathbf{b})$	probability of not removing a single nucleon by abrasion
p	number of abraded nucleons contributing to FSI
Q	droplet model coefficient (11.9 MeV)
R_P	uniform nuclear radius of projectile, fm
R_T	uniform nuclear radius of target, fm
r_0	uniform nuclear radius parameter (1.2 fm)
u	defined in equation (13)
x	distance into prefragment, fm
$\mathbf{y}$	two-nucleon relative position, fm
Z	total number of nuclear protons
Z_i	total number of nuclear protons for *ith* nucleus
z	number of abraded protons
$\mathbf{z}_0$	longitudinal position of target center of mass in projectile rest frame, fm
$\binom{A}{m}$	binomial coefficient
α_{ij}	probability of formation of type-i fragment as a result of deexcitation of type-j prefragment
α_Z	defined in equation (12)
β	defined in equation (20)
Δ	excess nuclear surface area, fm^2
θ	orientation angle, rad
λ	mean free path, fm
μ	defined in equation (21)
ν	defined in equation (19)
ξ_P	collection of constituent relative coordinates for projectile, fm
ρ	nuclear density, fm^{-3}
ρ_P	projectile nuclear density, fm^{-3}
ρ_T	target nuclear density, fm^{-3}
$\sigma(e)$	average nucleon-nucleon total cross section, mb
$\sigma_{\text{abr}}(Z_j, A_j)$	cross section for production of nucleus of type (Z, A) by abrasion, mb
$\sigma_{\text{abr}}(Z, A, p)$	abrasion cross section for nucleus of type (Z, A) which has had p FSI interactions, mb

σ_{EM} Coulomb dissociation cross section, mb

σ_F fragmentation cross section, mb

σ_m cross section for abrading m nucleons, mb

σ_{NN} defined in equation (32)

σ_{nuc} final nuclear fragmentation cross section, mb

σ_Z element production cross section, mb

TABLE I. ISOTOPE PRODUCTION CROSS SECTIONS FROM TARGET FRAGMENTATION FOR THE REACTION $^{12}C + {}^{12}C \rightarrow A_Z + X$

[Incident kinetic energy is 2.1 GeV/nucleon]

Isotope produced	Isotope production cross sections, mb		
	Hypergeometric model	Giant dipole resonance model	Experiment (ref. 13)
^{11}C	56.4	56.4	[a]60.9 ± 0.6
			46.5 ± 2.3
^{10}C	28.9	13.7	4.11 ± 0.22
^{9}C	8.2	1.6	0.539 ± 0.066
^{11}B	56.4	56.4	53.8 ± 2.7
^{10}B	23.4	31.0	35.1 ± 3.4
^{9}B	52.3	61.8	
^{8}B	18.3	13.4	1.72 ± 0.13
^{7}B	6.8	1.8	
^{10}Be	29.2	14.0	5.81 ± 0.29
^{9}Be	51.1	59.9	10.6 ± 0.5
^{7}Be	46.8	54.1	18.6 ± 0.9
^{9}Li	8.2	1.6	0.851 ± 0.082
^{8}Li	18.3	13.4	2.18 ± 0.15
^{7}Li	32.0	55.9	21.5 ± 1.1
^{6}Li	69.3	86.1	30.0 ± 2.4

[a]Value from reference 14.

TABLE II. ISOTOPE PRODUCTION CROSS SECTIONS FROM TARGET FRAGMENTATION FOR THE REACTION $^{20}\mathrm{Ne} + {}^{12}\mathrm{C} \rightarrow A_Z + X$

[Incident kinetic energy is 1.05 GeV/nucleon]

Isotope produced	Isotope production cross sections, mb		
	Hypergeometric model	Giant dipole resonance model	Experiment (ref. 15)
^{11}C	65.3	65.3	80.3 ± 1.4
^{10}C	32.7	16.6	
^{9}C	9.4	2.0	
^{11}B	65.4	65.4	
^{10}B	27.3	35.4	
^{9}B	60.2	70.6	
^{8}B	20.7	15.6	
^{7}B	8.0	2.2	
^{10}Be	32.8	16.7	
^{9}Be	57.3	67.8	
^{8}Be	54.1	60.0	
^{9}Li	9.4	2.0	
^{8}Li	20.7	15.6	
^{7}Li	57.4	64.5	
^{6}Li	79.7	99.0	

TABLE III. ISOTOPE PRODUCTION CROSS SECTIONS FROM TARGET FRAGMENTATION FOR THE REACTION $^{56}Fe + ^{12}C \rightarrow A_Z + X$

[Incident kinetic energy is 1.7 GeV/nucleon]

Isotope produced	Isotope production cross sections, mb		
	Hypergeometric model	Giant dipole resonance model	Experiment (ref. 15)
^{11}C	85.5	85.5	99.5 ± 1.5
^{10}C	40.5	22.0	
^{9}C	11.8	2.8	
^{11}B	86.1	86.1	
^{10}B	33.5	42.7	
^{9}B	73.9	85.4	
^{8}B	25.6	20.1	
^{7}B	10.0	6.0	
^{10}Be	40.7	22.2	
^{9}Be	70.6	81.8	
^{7}Be	68.5	75.4	
^{9}Li	11.8	2.8	
^{8}Li	25.6	20.1	
^{7}Li	71.4	79.5	
^{6}Li	97.6	121.0	

TABLE IV. REPRESENTATIVE ISOTOPE PRODUCTION CROSS SECTIONS FROM COPPER FRAGMENTATION IN THE REACTION $p + {}^{64}\mathrm{Cu} \rightarrow A_Z + X$

[Incident proton kinetic energy is 3.9 GeV]

Isotope produced	Isotope production cross sections, mb	
	Hypergeometric model	Experiment (ref. 16)
^{63}Cu	66.2	14.3 ± 0.7
^{62}Cu	11.8	
^{61}Cu	14.8	11.5 ± 0.4
^{60}Cu	13.1	1.92 ± 0.6
^{63}Ni	54.8	
^{62}Ni	20.0	
^{61}Ni	23.8	
^{60}Ni	69.9	
^{59}Ni	33.4	
^{58}Ni	10.4	
^{62}Co	8.0	0.51 ± 0.04
^{61}Co	7.5	4 ± 0.08
^{60}Co	14.9	8.34 ± 0.09
^{59}Co	22.2	
^{58}Co	29.3	20.6 ± 0.2
^{57}Co	23.0	16.9 ± 0.1
^{56}Co	15.6	5.6 ± 0.3
^{59}Fe	3.9	1.33 ± 0.24
^{53}Fe	1.9	1.83 ± 0.22
^{56}Mn	6.7	2.58 ± 0.08
^{54}Mn	15.1	13.8 ± 0.2
^{52}Mn	7.6	6.26 ± 0.08

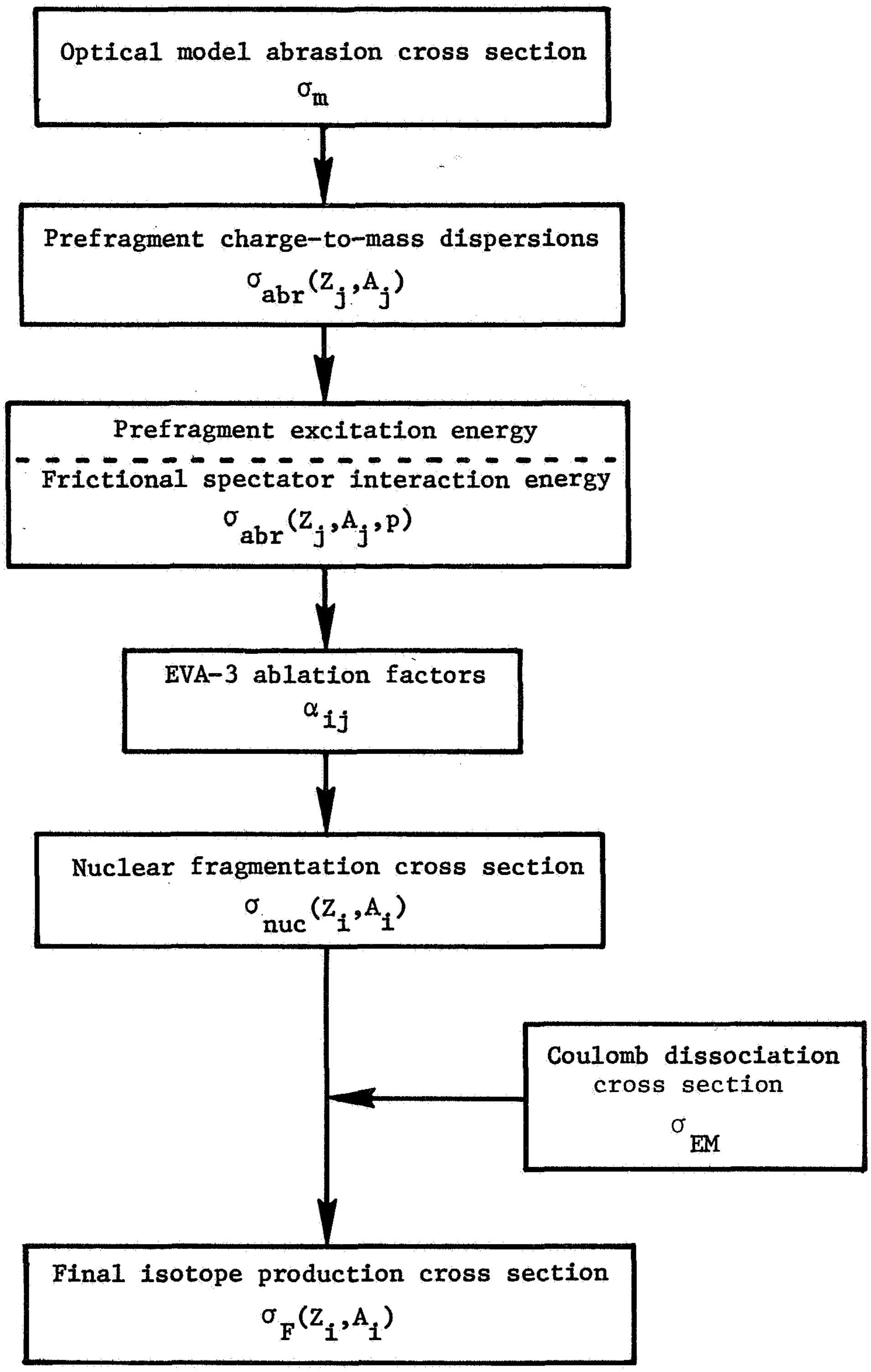

Figure 1. Flow diagram of steps in target fragmentation calculation.

Standard Bibliographic Page

1. Report No. NASA TM-87692	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Optical Model Calculations of Heavy-Ion Target Fragmentation		5. Report Date July 1986
		6. Performing Organization Code 199-22-76-01
7. Author(s) Lawrence W. Townsend, John W. Wilson, Francis A. Cucinotta, and John W. Norbury		8. Performing Organization Report No. L-16113
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

Lawrence W. Townsend and John W. Wilson: Langley Research Center, Hampton, Virginia.
Francis A. Cucinotta and John W. Norbury: Old Dominion University, Norfolk, Virginia.

16. Abstract

The fragmentation of target nuclei by relativistic protons and heavy ions is described within the context of a simple abrasion–ablation–final-state interaction model. Abrasion is described by a quantum mechanical formalism utilizing an optical model potential approximation. Nuclear charge distributions of the excited prefragments are calculated by both a hypergeometric distribution and a method based upon the zero-point oscillations of the giant dipole resonance. Excitation energies are estimated from the excess surface energy resulting from the abrasion process and the additional energy deposited by frictional spectator interactions of the abraded nucleons. The ablation probabilities are obtained from the EVA-3 computer program. Isotope production cross sections for the spallation of copper targets by relativistic protons and for the fragmenting of carbon targets by relativistic carbon, neon, and iron projectiles are calculated and compared with available experimental data.

17. Key Words (Suggested by Authors(s)) Target fragmentation; Galactic heavy-ion shielding; HZE particles; Abrasion-ablation model	18. Distribution Statement Unclassified—Unlimited; Subject Category 73

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	13	A02

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1986

National Aeronautics and
Space Administration
Code NIT-4

Washington, D.C.
20546-0001

Official Business
Penalty for Private Use, $300

BULK RATE
POSTAGE & FEES PAID
NASA
Permit No. G-27

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return